

# Towards 21st Century Stellar Models: Star Clusters, Supercomputing and Asteroseismology,<sup>\*</sup>

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Stellar models provide a vital basis for many aspects of astronomy and astrophysics. Recent advances in observational astronomy – through asteroseismology, precision photometry, high-resolution spectroscopy, and large-scale surveys – are placing stellar models under greater quantitative scrutiny than ever. The model limitations are being exposed and the next generation of stellar models is needed as soon as possible. The current uncertainties in the models propagate to the later phases of stellar evolution, hindering our understanding of stellar populations and chemical evolution. Here we give a brief overview of the evolution, importance, and substantial uncertainties of core helium burning stars in particular and then briefly discuss a range of methods, both theoretical and observational, that we are using to advance the modelling.

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## 1 Introduction

### 1.1 On the importance of accurate stellar models

Stellar models provide various predictions that are widely used in other fields of astrophysics. For example, they give lifetime predictions for each phase of evolution (to be compared to star counts), surface properties such as temperature, luminosity, chemical abundances (to be compared to photometry and spectroscopy). They also predict contributions to the interstellar medium (ISM) versus time through stellar mass-loss via winds and explosions, which release newly formed chemical elements and electromagnetic radiation. Apart from the external properties and ISM contributions stellar models also provide internal stellar properties: thermal structure, chemical profiles, asteroseismic properties, for example. Many of these outputs are key inputs for models of Galactic evolution and are central to age determinations of stars, both of which are important for deciphering the processes behind the formation and evolution of the Milky Way and other galaxies. Any uncertainties in the

stellar models have ‘knock-on’ effects in the understanding of stellar populations. With the recent advances in observational astronomy – through asteroseismology, precision photometry, high-resolution spectroscopy, and large-scale surveys – accurate stellar models are under greater quantitative scrutiny than ever. Here we focus on one of the stages of evolution that is currently poorly modelled: the core helium-burning (CHeB) phase.

### 1.2 Overview of core helium burning stars

Known observationally as red clump, second clump, horizontal branch (HB), subdwarf B, or RR Lyrae stars – depending on metallicity, envelope mass, and total mass – CHeB stars are numerous and relatively luminous and therefore contribute disproportionately to Galactic (and extragalactic) emission. CHeB occurs between the first/red giant branch (RGB) and the second/asymptotic giant branch (AGB) phase. Lifetimes of CHeB stars are  $\sim 1$  to 10% of the main sequence lifetimes. Their internal structure is characterised by dense cores that are (initially) mainly composed of helium ( $\sim 98\%$  by mass, left over from core hydrogen burning), a radiative zone above containing a H-burning shell, and then a convective envelope (see Fig. 1). Helium

<sup>\*</sup> This study uses observational data from HST, VLT, AAT, Kepler, and supercomputing resources at iVEC and NCMAS.

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burning occurs in the convective core and produces C and O. These ‘ashes’ become the C-O cores of AGB stars and eventually the remnant white dwarves. Subsequent evolutionary channels of the models, eg. AGB, planetary nebulae, supernovae, is dependent on the results of this phase, so it is important to simulate this phase well. Unfortunately, CHeB is where stellar code results start to diverge significantly, undermining the accuracy of models of supernova explosions and red giants – both vital to the chemical evolution of the Galaxy.

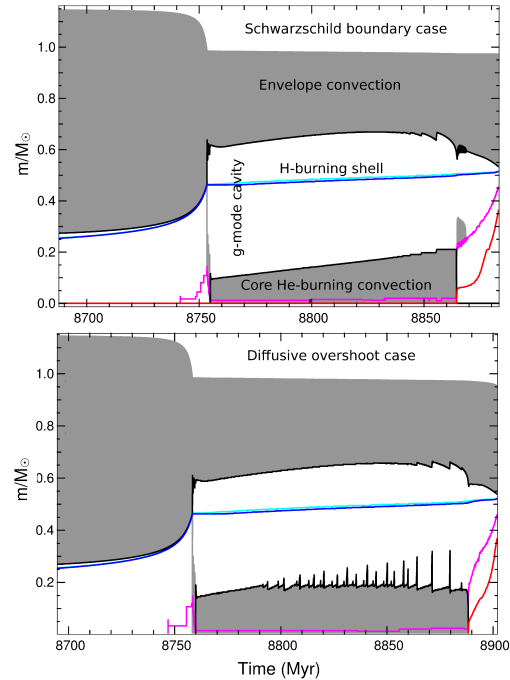
In this paper we first highlight the uncertainties in the current generation of CHeB models and then briefly outline some of the ongoing efforts to improve them.

## 2 Current state of CHeB modelling

Stellar codes can give wildly varying evolution results for core helium burning. In a code comparison between four stellar codes (2007, private communication) it was found for a  $5 M_{\odot}$  star that (i) lifetimes differ by up to a factor of two (from  $\sim 13$  to  $26$  Myr), and (ii) final core masses vary by similar amounts (from  $\sim 0.17$  to  $0.45 M_{\odot}$ ). The uncertainty holds for massive star models ( $M > 10 M_{\odot}$ , eg. Langer 1991), so it affects (pre)supernova models and multidimensional simulations that use 1D models as initial structures. Some of the discrepancies arise from inconsistent application of the criteria for convective stability (see Gabriel et al. 2014 for an analysis) and numerical treatment (eg. top panel of Fig. 1). The discordance of the models points to the fact that we do not yet know how to properly treat convective boundaries reliably. Moreover CHeB is a particularly difficult case since an opacity disparity between the convective core and the radiative zone above builds as helium burning converts He to C and O. Results from stellar codes are heavily dependent on the treatment of mixing adopted for the edge of the convective core. As an example we show in Figure 1 a pair of our models that differ only in convective zone boundary treatment (see also Fig. 15 in Paxton et al. 2013). The ‘spikes’ seen in the lower panel (diffusive overshoot case) are ‘core breathing pulses’ – sudden ingestions of helium from the radiative zone due to the numerical instability of the convective boundary. This mixing reduces the size of the fully mixed core as compared to the model with no overshooting. From an asteroseismic point of view this will affect the oscillation frequencies since the g-mode cavity is different. This is discussed further below.

## 3 Efforts to improve CHeB models

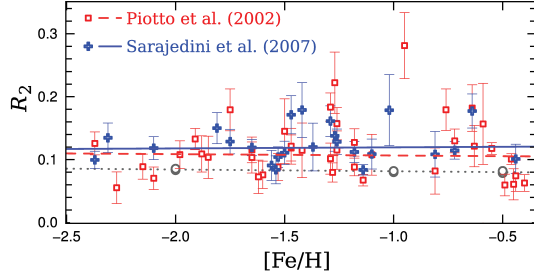
Our approach to improve CHeB modelling is to use both observations and theory to inform and constrain the models. Here we give a brief outline of some of our ongoing work.



**Fig. 1** Example of the effects of using different convective boundary treatments on CHeB evolution in the same stellar evolution code (in this case the Monash stellar code MONSTAR; see eg. Campbell & Lattanzio 2008). Both models have an initial mass  $1.15 M_{\odot}$  and metallicity  $Z = 0.03$ . Apart from the core boundary treatment all other inputs are identical. Grey shading represents convective regions. **Top panel:** Schwarzschild boundary with no overshoot. We note that there is some core growth in this model. A ‘strict’ implementation of the Schwarzschild criterion would result in no core growth: see Fig. 2 in Constantino et al. 2015 for an example using the same code. The core growth here is due to the numerical treatment at the convective core boundary. This further highlights the difficulties of modelling this phase of evolution (see also Gabriel et al. 2014). **Bottom panel:** Schwarzschild boundary with diffusive overshoot. Note the stochastic behaviour of the core boundary in the overshoot case.

### 3.1 Star clusters: Spectroscopic observations

Galactic globular clusters (GC) have long been used to constrain stellar models. Their colour-magnitude diagrams (CMD) show tight evolutionary sequences, indicating that they are relatively uniform stellar populations. Almost all GCs have constant star-to-star abundances of Fe group elements indicating that the clusters were well-mixed when the stars formed. However spectroscopic observations of the light elements (eg. C, N, O, Na) have revealed that practically all GCs contain at least two chemically distinct populations (eg. Norris et al. 1981, Gratton et al. 2012). The differences in light-element abundance patterns has been shown to extend down to the main sequence, indicating that



**Fig. 2** Number ratio of AGB stars to CHeB stars ( $R_2$ ) versus metallicity for 48 GCs. HST photometry is taken from Piotto et al. (2002) and Sarajedini et al. (2007), as labelled. The dotted line gives an indication of the offset from current models, in this case using the semiconvection boundary treatment. See Constantino et al. (2016) for more details

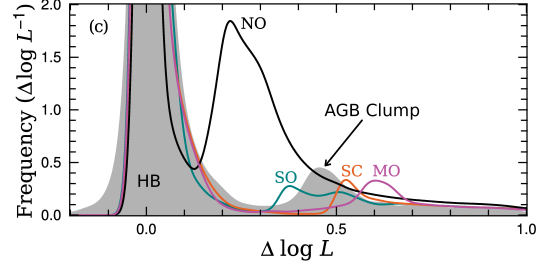
the composition distribution must have been in place at the earliest times of GC evolution (eg. Cannon et al. 1998).

The ongoing puzzle of the origins of the GC multiple populations can be seen as smaller-scale versions of Galactic-scale star formation problems, especially in chemical space. For example the ‘Chemical Tagging’ technique (Freeman & Bland-Hawthorn 2002), which quantifies the level of chemical homogeneity across individual elements in a stellar population, can be used to trace the origin of Galactic substructure (De Silva et al. 2006). Although making GCs more complex than initially thought, the existence of multiple populations also opens up other opportunities to study stellar evolution, since the populations are still much more homogeneous than field star populations. To exploit this we have made a chemical tagging study of the subpopulations of NGC 6752 at different evolutionary phases. This showed that stars of particular composition fail to get to the AGB phase. Instead they appear to exit to the WD cooling track directly from the CHeB phase, since stars with high Na are not seen on the AGB. In the case of NGC 6752 70% of the cluster stars take this evolutionary path (Campbell et al. 2013). Standard stellar models cannot reproduce this (Campbell et al. 2013, Cassisi et al. 2014) and it represents another shortcoming of CHeB models.

### 3.2 Star Clusters: Photometric observations

In Figure 2 we show our results using star counts of CHeB and AGB stars in HST photometry of 48 GCs. The number ratio of AGB to HB (CHeB) stars  $R_2 = N_{AGB}/N_{HB}$  is directly related to the relative lifetimes of the two phases. We find that  $R_2 = 0.117 \pm 0.005$ , substantially lower than typical previous determinations. Interestingly, the result is consistent with  $R_2$  being single-valued across all GCs. This value is more consistent with some models in the literature, although it is still somewhat high compared to standard models (see eg. dotted line in Fig. 2).

In Figure 3 we show another constraint from photometry that models must account for, the AGB clump. The observa-

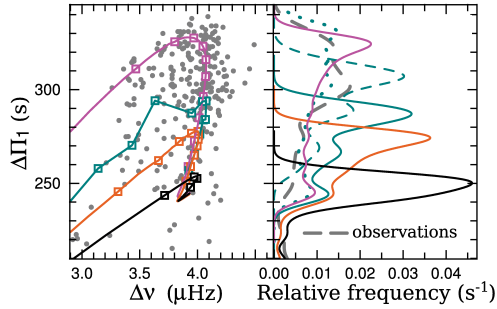


**Fig. 3** Observed average luminosity distribution for 13 GCs that do not have an extreme blue extension of their HB (grey shading) and also for four stellar models (lines) that differ in convective boundary treatment. The models are labelled: NO = no overshoot; SO = standard overshoot; SC = semiconvection; MO = maximal overshoot.  $\Delta \log L$  is the luminosity difference to the centre of the HB peak. None of the models satisfactorily match the observations. Image adapted from Constantino et al. (2016).

tions present a remarkably sharp peak given that the data is from a host of different GCs and that there is a range of observational uncertainties, both of which would tend to widen the peak. Thus this observation is a particularly strong constraint on models. We also show the effect of using different boundary treatments during CHeB modelling in the figure. None of the models satisfactorily reproduce the observation and only the model with no overshoot can be ruled out definitively. This is another problem for the CHeB modelling, and highlights the need for multiple constraints. See Constantino et al. (2016) for more details on this study.

### 3.3 Asteroseismology

Asteroseismology presents a unique opportunity to provide information on the interiors of stars. Data from the Kepler and CoRoT space telescopes have revealed the presence of oscillation modes of mixed g- and p-mode character in RGB and CHeB stars (eg. Bedding et al. 2011). The g-mode signatures allow inferences on the core structure of stars. We have investigated the pulsation characteristics of a suite of CHeB stellar models using a variety of core boundary mixing treatments (Constantino et al. 2015; also see Bossini et al. 2015), and compared these to the mixed-mode period spacings ( $\Delta \Pi_1$ ) for CHeB stars deduced from Kepler data (Mosser et al. 2014). Pulsation characteristics of CHeB stars depend strongly on core size and chemical profiles, both of which are affected by the convective boundary treatment used. We found that standard models (employing the usual overshoot or semiconvection treatments) cannot match the mixed-mode period spacings. Only a new mixing routine, ‘maximal overshoot’ (MO) comes close to observations (Constantino et al. 2015). In Figure 4 we show a comparison between the asteroseismic observations and models. Although we can match the peak of the distribution with the MO model, we include no physical basis for such a large extension of the convective core. Also, none



**Fig. 4** Comparison between our suite of models and asteroseismic observations of CHeB stars.  $\Delta\Pi_1$  is the g-mode period spacing and  $\Delta\nu$  is the large frequency separation. CHeB models with four different convective boundary mixing schemes are shown: no overshoot (black), standard overshoot (cyan), semiconvection (orange), and maximal overshoot (magenta). Each model has an initial mass  $1 M_\odot$ . **Left panel:** Lines show the evolution of the models, with markers at 10 Myr intervals. Grey dots show observations (Kepler field stars from Mosser et al. 2014), and are limited to those with reported mass  $0.8 < M/M_\odot < 1.25$ . **Right panel:** Probability density curves for the models and observations.

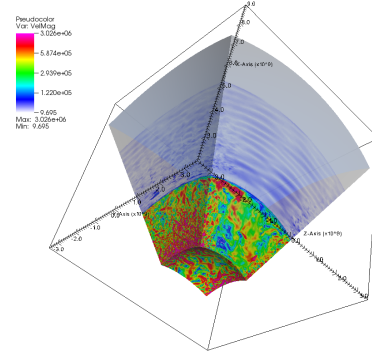
of the models can match the distribution at lower  $\Delta\Pi_1$ . Another possible solution to the mismatch between the models and observations is that the assumptions in observationally-determined values may be wrong, thereby skewing the distribution. There is still great potential in using asteroseismology to constrain the models. It is however very important to know the observational sample biases in order to make strong conclusions on stellar structure.

### 3.4 Supercomputing: 3D Hydrodynamics models

The key problems with CHeB models are related to the treatment of convection and convective boundaries – both crudely modelled in 1D at the moment. 3D hydrodynamics models have the potential to provide physical insights into these processes (see eg. Meakin & Arnett 2007, Viallet et al. 2015). This new knowledge could then be used in the 1D models (‘321D’, eg. Meakin & Arnett 2007, Arnett et al. 2015), which are still necessary for simulating the whole lifetime of a star. The 3D models are still hugely computationally expensive but it is possible to now simulate a few convective turnover times at low resolution (compared to the resolution needed to resolve all scales of turbulence). Using the stellar hydrodynamics code PROMPI (Meakin & Arnett 2007) we have begun a simulation of the CHeB phase in an  $8 M_\odot$  star (Fig. 5).

## 4 Summary

It is critical to model stars well since the uncertainties in the stellar models will affect the interpretation of a range



**Fig. 5** Snapshot of one of our 3D stellar hydrodynamics calculations. This simulation models the turbulent convection deep inside the helium-burning core of an  $8 M_\odot$  star. Colour scale is velocity magnitude (cm/s). The regular wave pattern in the stable gas above the turbulent core are gravity waves. Spatial axes are in centimetres.

of observations, and feed back on the modelling and understanding of stellar populations. Given the current uncertainty of CHeB modelling we advise caution when grids of stellar models are used in Galactic modelling, particularly for the late phases of stellar evolution. At least 4 different problems have been identified for CHeB stars here. Initial work in improving/constraining the models is revealing that: (i) it is very difficult to simultaneously match multiple observational constraints, (ii) biases in observational samples need to be reported so the data can be used to reliably constrain models. All the work mentioned in this paper is ongoing. Also of interest here is the recent analytical work by Spruit (2015) who estimates the entrainment rate of He at the convective boundary of CHeB stars, which he finds is primarily a function of the convective luminosity. This will need to be included in stellar structure calculations and compared to observations.

Finally, we are also working on a unique opportunity provided by the new Kepler space telescope mission K2 – the seismic observation of a globular cluster (M4). Here we aim to combine photometry, spectroscopy and asteroseismology in a well-characterised and (relatively) uniform stellar population. We now have K2 light curves and high-resolution optical spectra collected with the HERMES spectrograph (Sheinis et al. 2015; AAT) for a sample of stars at various evolutionary stages.

## References

- Arnett, W.D., Meakin, C., Viallet, M., et al. 2015, *ApJ*, 809, 30
- Bedding T. R., Mosser, B., Huber, D., et al. 2011, *Nature*, 471, 608
- Bossini, D., Miglio, A., et al. 2015, *MNRAS*, 453, 2290
- Campbell, S.W., D’Orazi, V., et al. 2013, *Nature*, 498, 198
- Campbell, S. W., Lattanzio, J. C. 2008, *A&A*, 490, 769
- Cannon, R.D., Croke, B.F.W., Bell, R.A. 1998, *MNRAS*, 298, 601
- Carretta, E., Bragaglia, A., et al. 2007, *A&A*, 464, 927
- Cassisi, S., Salaris, M., et al. 2014, *A&A*, 571A, 81
- Constantino, T.N., Campbell, S.W., et al. 2015, *MNRAS*, 452, 123

- Constantino, T.N., Campbell, S.W., et al. 2016, MNRAS, submitted
- De Silva, G.M., Sneden, C., et al. 2006, AJ, 131, 455
- Freeman, K., Bland-Hawthorn, J. 2002, ARA&A, 40, 487
- Gabriel, M., Noels, A., Montalbán, J., et al. 2014, A&A, 569A, 63
- Gratton, R.G., Carretta, E., Bragaglia, A. 2012m A&ARv, 20, 50
- Langer, N. 1991, A&A, 248, 531L
- Meakin, C.A., Arnett, D. 2007, ApJ, 667, 448
- Mochejska, B.J., Kaluzny, J., et al. 2002 AJ, 124, 1486
- Mosser, B., Benomar, O., Belkacem, K., et al. 2014, A&A, 572, 5
- Norris, J., Cottrell, P.L., et al. 1981, ApJ, 244, 205
- Paxton, B., Cantiello, M., Arras, P., et al. 2013, ApJS, 208, 4
- Piotto G., King, I.R., Djorgovski, S.G., et al. 2002, A&A, 391, 945
- Sarajedini A., Bedin, L.R., Chaboyer, B., et al. 2007, AJ, 133, 1658
- Sheinis A., Anguiano, B., et al. 2015, JATIS, 1(3), 035002
- Spruit, H.C. 2015, A&A, 582L, 2
- Viallet, M., Meakin, C., Prat, V., Arnett, D. 2015, A&A, 580, 61